DOCUMENT RESUME

ED 294 163 CS 009 152

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TITLE Technological Advances and the Study of Reading.
PUB DATE 12 Nov 87
NOTE 48p.
PUB TYPE Reports - Research/Technical (143) -- Information Analyses (070)

EDRS PRICE MF01/PC02 Plus Postage.
DESCRIPTORS *Computers; Dyslexia; Eye Fixations; Identification; *Neurology; Reading Ability; Reading Diagnosis; *Reading Difficulties; Reading Instruction; *Reading Processes; Reading Research; Scientific and Technical Information; *Technological Advancement
IDENTIFIERS Brain Research; Brain Waves; Computerized Techniques; Neuroanatomy; *Psychoneurological Assessment; Topographic Brain Mapping; X Rays

ABSTRACT

Recent technological advances in neuroanatomy and neurophysiology have unearthed structural and functional patterns in the brain that can be associated with severe reading disabilities. As a response, this paper examines several computer-driven technologies whose capabilities shed light on brain-related issues germane to reading, with the intent of preparing reading professionals for the impact which technology may soon exert on diagnostic and instructional reading endeavors. Technologies discussed in the paper are: (1) x-ray monitoring techniques; (2) radioactive isotope imaging; (3) magnetic resonance imaging; (4) brain wave monitoring; and (5) eye tracking. The paper assesses each technology as to cost, invasiveness, success at imaging brain tissue, provision of anatomical and functional data, and capacity to provide real time data. The paper argues that because of these new technologies, reading educators may soon engage in more productive collaborations with neuroscientists, but that not all of the answers reading educators seek are to be provided by these technologies. The paper concludes that issues such as optimum grouping procedures, classroom management, and discipline lie outside the technological realm. (Nine pages of references are attached.) (MHC)

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Technological Advances and the Study of Reading

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November 12, 1987

Running head: Technology and Reading

CS009152

Abstract

Recent years have witnessed the development of several new computer-driven technologies whose capabilities shed light on brain-related issues germane to the field of reading. This paper describes the purpose and functional operation of these technologies, outlines their current contribution to our knowledge base, and provides some speculation regarding the role existing and emerging technologies will play in future diagnostic and instuctional reading endeavors. Included among the technologies are computerized axial tomography (CAT), Positron Emission Transaxial Tomography (PETT), regional cerebral blood flow (rCBF) monitoring, Magnetic Resonance Imaging (MRI), Brain Electrical Activity Mapping (BEAM), and sophisticated eye tracking systems.

Technological Advances and the Study of Reading

In 1908 the rather recently-heralded American psychologist, E. B. Huey, suggested that a complete understanding of the reading process would reveal the innermost workings of the human mind. He argued that such an understanding would lay bare the brain's seemingly countless mysteries not the least of which included attention, perception, imagery, memory, and reasoning. Huey's cogent assertion brings to focus the obvious, yet often curiously neglected notion that reading and the brain are necessarily bound to one another. Simply put, the brain is the organ for reading (Hart, 1975, 1983). So while Huey would endeavor to understand reading as a means for knowing the brain, stunning technological advances in neuroanatomy and neurophysiology are instead already contributing to our understanding of the reading process (Hynd & Hynd, 1984).

Specifically, these computer-driven technologies offer the promise of more precise reading diagnoses and increased instructional effectiveness, particularly in the case of neurologically-impaired, developmentally delayed, or dyslexic individuals. The methods, which employ the monitoring of X-rays, cerebral blood flow, hydrogen atoms, brain wave activity, and eye movements, have already unearthed structural and functional patterns in the brain

that can be reasonably associated with severe reading disabilities.

This paper 1) examines several of these computer-driven technologies including Computerized Axial Tomography, Positron Emission Transaxial Tomography, regional cerebral blood flow monitoring, Magnetic Resonance Imaging, Brain Electrical Activity Mapping, and sophisticated eye tracking systems, 2) outlines their operation and current capabilities, and 3) offers some forecasts for their future in our quest to understand the psychological processes underlying the reading act.

The broader intent of this paper is to prepare reading professionals for the impact these technologies may soon exert on the field. For example, in the not too distant future, some technologies will be used routinely to identify potential at-risk children prior to any formal schooling. Obviously, this early identification capability could lead to significant benefits for the severely reading disabled. Most importantly, it would alert educators to potential problems and allow them to invoke alternative, preventitive programming. In the more distant future, these technologies and their successors will elevate reading research and practice to newfound heights and open novel directions for inquiry, perhaps in the form of better meeting the needs of average and gifted children.

Studying the Living Brain

As Torello and Duffy (1985) indicate, contemporary educators have come to embrace more fully the neuroscientific perspective that the brain is largely the source of severe individual learning dysfunctions. While behavioral and paper-pencil tests indicate the products of deficient cognition, they do not detect directly the brain activity or architecture associated with inefficient higher level processing. By monitoring the brain more directly, critical insights may be garnered regarding the etiology and nature of certain reading disabilities that could increase the effectiveness of remedial instruction. In this regard, neurophysiologists (Crick, 1979; Hubel, 1979), neuropsychologists (Hynd & Hynd, 1984), theorists (Hart, 1975; 1983), and educators (Chall & Mirsky, 1978) agree that the field of education will be affected if the mechanisms underlying learning and memory are revealed, an accomplishment that may very well be achieved with the help of these amazing new technologies. So whether one subscribes to the growing body of suggestive evidence linking brain abnormalities and reading disabilities (Hynd & Semrud-Clikeman, 1987a, 1987b), an awareness of these neuroimaging technologies may prove to be useful.

Were Huey alive today, he would no doubt marvel at the triumphs of engineering that have ushered in an unparalleled capacity to study the living brain. In his lifetime,

devices like those presently existing were the stuff of science fiction--barely imaginable considering the state of technology in that time period. Further, as Hynd and Hynd (1984) indicate, it has only been within recent years that medical science has been able to sustain life in brain-damaged patients, thereby making possible the study of the central nervous system following trauma. Huey's only, albeit profound, clue to what lie ahead would have been the development of X-ray technology by Wilhelm Rontgen in 1895.

Until very recently, most of what was known about language and the brain came from abnormal conditions such as those involving brain damage or brain surgery (Geschwind, 1972). Our earlier knowledge base emanated from such human traumas as strokes, war injuries, and epilepsy. For example, nineteenth century brain researchers Paul Broca (1861) and Carl Wernicke (1874) were able, by virtue of post-mortem examinations, to implicate two areas in the left hemisphere that were involved in the production and comprehension of speech. They did so by examining the brains of stroke victims who had displayed expressive and receptive language difficulties in life. Later, two chief neurosurgeons, Wilder Penfield of Canada (See Penfield & Rasmussen, 1950; Penfield & Roberts, 1959) and Otfrid Foerster of Germany (Geschwind, 1979), pioneered a technique whereby various sites in the brain of conscious patients undergoing necessary surgery were electrically stimulated.

By doing so, these surgeons were able to map the regions of the brain responsible for a number of motor and sensory functions. Still later, Roger Sperry and Michael Gazzaniga (See Gazzaniga, 1970; Sperry, 1968, 1973; Sperry & Gazzaniga, 1967) studied "split-brain" patients, individuals whose severe epileptic seizures prompted a surgical cutting of the corpus callosum, the major connection between the left and right hemispheres. From this research, the respective contributions of each cerebral hemisphere have come to be better understood (Wittrock, 1978).

While each of these lines of inquiry yielded findings of landmark proportions, the fact remains that none of them dealt with the examination of completely normal, living brains. That is to say, Broca and Wernicke were forced to study deviant brains in an inanimate state[1], and the others examined living brains that were in some way already impaired enough to warrant surgery. In particular, the patients of Sperry and Gazzaniga were, for all intents and purposes, physically maimed. Collectively, then, these historical attempts to gain insight into the workings of the brain suffered from the unavoidable scientific constraints associated with inferred relationships. However compelling and revelatory these findings may have been, they could not be generalized to individuals for whom the abnormal conditions were not in evidence.

As a result, neuropsychology remained a prisoner of speculation; progress was slow in coming, findings would be tentative, and the knowledge would possess only limited applicability. Without direct, naturalistic understandings of the brain's structures and operations, the psychological disciplines were forced to assume a form of indirect inquiry known as the black-box approach. Crick (1979) described the approach as follows: "The experimenter studies the inputs and outputs and tries from the results to deduce the structure and operation of the inside of the box... The difficulty with the black-box approach is that unless the box is inherently very simple a stage is soon reached where several rival theories all explain the observed results equally well." Crick goes on to say that trying to decide among the alternative explanations becomes even more problematic since findings of new studies continually introduce more complexities. Ultimately, then, if the matter is to be resolved, we must look inside the box. Fortunately, such observation is being made possible by a generation of striking new technologies that, however impressive, pale in comparison to the ultimate accomplishment of human bioengineering they seek to reveal.

The Ideal Imaging Device

If researchers could endow an imaging device with an ideal set of capabilities, what would the machines be able to do? Yingling (1987) suggests the following criteria.

First, the device should image the brain and not other tissues. Brain structures must be clearly demarcated and recorded faithfully to allow for easy interpretation and accurate observation. Second, the device must provide both anatomical and functional data about the brain. Whereas anatomy describes the various structures of the brain and the way they are connected, physiology seeks to determine how the elements function individually and in combination with one another (Crick, 1979). Knowing the structure without knowledge of the function would be analogous to a computer technician knowing all the internal parts of the apparatus, their locations, and their interconnections without knowing what contribution each part makes to the operation of the unit. In this sense, the ideal imaging device must provide evidence of architecture and activity. Further, the device would be simple to use and sufficiently inexpensive to allow for greater numbers of observations. For ethical reasons, the procedure must also be non-invasive, and therefore, entail minimal or no risk to the individual. This non-invasive aspect is especially important from a research standpoint because it permits the study of normal control subjects. Invasive procedures can only be justified when a suspected medical affliction makes imaging absolutely necessary. And lastly, the procedure must provide real time data; that is, phenomena should be evident as quickly as they occur in the individual's brain.

As Restak (1984) states, "no still picture or measurement of one specific moment can lead to an appreciation of the living brain. At all times, the brain is functioning as a whole. The goal, of course, is somehow to capture the brain in all its dynamism."

Which existing machine possesses all of these qualities? Unfortunately, none of them do. But this does not preclude the possibility that such a device will ever be developed. On the contrary, the incredible rate of technological advancement portends the eventual development of just such an imaging system. For the time being, however, each of the technologies to be described here meets certain of the criteria to varying extents and these capabilities and constraints will be detailed in subsequent sections.

The Technologies

X-Ray Monitoring Techniques

For years, the absence of methods for studying the living brain hindered investigations of brain disorders. Then at the end of the nineteenth century, X-ray technology emerged. While X-rays certainly represented a major boon to the medical profession, the technology suffered from the fact that the projections of abnormalities on the developed film often overlapped those of normal structures. Consequently, distinguishing between neighboring normal and

abnormal structures of similar densities proved to be extremely difficult and occasionally even impossible to achieve (Kety, 1979).

CAT scans improve upon standard X-ray technology by generating enhanced pictures of brain structures. More specifically, CAT scans combine X-ray readings derived from many different angles to produce a depiction of the living brain's internal structures in cross section. To obtain the representation, the head of a subject who has received a veinal injection of an iodine solution is placed into a doughnut shaped scanner. Above the head, an X-ray tube rotates along a circular path sending thin X-ray beams at one degree intervals over a 180 degree arc. Like normal X-rays, the brain tissue absorbs the radiation according to the density of its varying parts. Modified by these local variations in density, the beams emerge to strike sensitive crystal detectors on the opposite side of the circular chamber. The detectors convert the beams to electronic signals that are, in turn, fed to a computer. The computer then calculates the difference between the amount of radiation originally emitted and the amount striking the detectors. Based on these calculations, the computer constructs a single cross-sectional image called a tomogram on a television screen. To enhance the assessment, additional layer by layer scans can be made by varying the angles of the original X-ray beam. The value of CAT scans

is that they reveal blood clots, tumors, and birth defects, as well as enlarged and atrophied normal structures (Kety, 1979; The Brain, 1982). Intuition suggests that any and perhaps all of these peculiarities may contribute to reading disability, and although the evidence is somewhat controversial and perhaps unreliable (Hynd & Hynd, 1984; Hynd & Semrud-Clikeman, 1987a, 1987b), numerous researchers using CAT scan technologies (Haslam, Dalby, Johns, & Rademaker, 1981; Hier, LeMay, Rosenberger, & Perlo, 1978; Rosenberger & Hier, 1980) have presented data linking neurological abnormalities to dyslexics. In this regard, the most reliable finding is that dyslexics evidence increased patterns of posterior brain symmetry or even reversed asymmetry wherein the size of structures in the right hemisphere exceed those in the left (Hynd & Semrud-Clikeman, 1987a, 1987b).

Just as the CAT scan improved upon standard X-ray technology, a new and more sophisticated system, the dynamic spatial reconstructor (DSR), figures to make an expanded contribution to observing brain structures and functions. Instead of displaying only slices of the brain as CAT scans do, the DSR reveals it in a three-dimensional representation that pulses with activity. Dynamic spatial reconstructors use 28 revolving X-ray guns to produce some 75,000 images in a mere five seconds, an amount exceeding the capacity with which computerized axial tomography can deal (The Brain,

1982). The heightened precision of DSR promises to help resolve the controversy surrounding CAT scan data that implicate neurological abnormalites in dyslexic children. At present, relatively few DSR units are in operation and so empirical data pertaining to reading are scarce. However, as the prevalence of DSRs increases, the precision with which brain architecture and activity can be measured will contribute more frequently to the diagnosis of reading-related disorders.

Radioactive Isotope Imaging: PETT, SPECT, and rCBF

Positron Emission Transaxial Tomography (PETT) Scans. Unlike CAT scans, PETT scans work by monitoring human brain metabolism. Measurements of the brain's metabolism have been made possible by the advent of radioactive isotopes that can be introduced to the brain through intravenous injections or through inhalation. In positron emission transaxial tomography, the radioactively-tagged substance is carried to the brain and then tracked by means of instruments that detect and measure the decay of the isotope. These measurements of brain metabolism are believed to provide an indirect indication of what structures are active and when they are active (Restak, 1984).

Like CAT scans, PETT technology involves placing the subject's head into a doughnut shaped chamber. The radiation that is emitted and detected in PETT scans,

however, comes from the brain itself rather than from some external source. Near the chamber, a substance such as glucose is tagged with a radioisotope brewed in a compact, low-energy cyclotron (an accelerator in which particles are propelled by an alternating electric field in a constant magnetic field). The isotope-bearing solution is injected into the body emitting positrons wherever it travels. The positrons collide with electrons and the two annihilate one another, thereby releasing energy bursts in the form of two gamma rays. The two gamma rays head in opposite directions striking crystal detectors encircling the subject's head. The activated crystals allow a computer to record the location of each flash, plot the source of the radiation, and convert the data (some five million bits per second during the entire length of the scan) into a cross-sectional colored graphic image. Areas of irregular brain activity are implicated by tracing the flow of the radioactive substance on the cathode ray tube (CRT) monitor. PETT's colored biochemical map of the brain exposes how injury or illness alters local blood flow or metabolic activity (Restak, 1984; Sochurek, 1987; The Brain, 1982).

At present, routine use of PETT scans in reading diagnosis is not possible. Most importantly, PETT scans are highly radioactive, and therefore, can only be made when some benefit can be shown to the individual. They are also very expensive because the short shelf-life of the

radioactive isotopes necessitates that the mixtures be created on site and used immediately. The total expense of three million dollars (1.5 million each for the PETT equipment and the cyclotron) makes the system unavailable in the majority of clinical settings ("SPECT Images'", 1987). Another drawback is that PETT scans cannot study rapidly changing behavior. For instance, they require that the individual maintain the same cognitive state for some 30 minutes before the radioactively-tagged glucose becomes detectable by the sensors. Some researchers have even questioned the link between cognition and energy consumption and have suggested that, relatively speaking, PETT scans provide somewhat limited resolution (Torello & Duffy, 1985).

Still, PETT scans are important because they attempt to get at brain functions rather than brain structures. It is the operation of the brain that figures to prove most enlightening with regard to reading diagnosis. Further, PETT scans are versatile; they merely involve finding a molecule that will carry positrons into the brain (Yingling, 1987). So while in their present form PETT scanning technologies are far from ideal, they may well serve as prototypes for future systems that will more precisely and rigorously monitor the activity of the brain. Thus far, only Gross-Glenn et al. (1987) have made use of PETT scanning in reading-related research. These researchers compared dyslexics and non-dyslexics and found bihemispheric

activation above baseline during the reading of controlled text.

Regional Cerebral Blood Flow (rCBF). Another radioisotope method, regional cerebral blood flow, has already proven enormously useful in examining various aspects of the reading process. This technology is also based upon the assumption that the relative level of blood in a region of the brain apparently indicates the current metabolic rate and functional activity of that area. Such a trend occurs, according to the developers of the technique, Neils Lassen, David Ingvar, and Erik Skinhøj, because the functional level of a tissue is strongly related to its oxygen uptake; that is, the bloodstream carries increased amounts of oxygen in response to elevated nerve cell activity and metabolism in specific brainsites (Lassen, Ingvar, & Skinhøj, 1978).

Like PETT scans, researchers can localize the functions of the cerebral cortex by injecting a radioactive isotope (xenon 133) into the individual. In rCBF technology injections are made into the carotid artery and regional blood flow is monitored during sensory, motor, or cognitive tasks. The blood flow is measured by means of a gamma-ray camera comprising 254 scintillation detectors placed near the head. Each of the detectors reports the local blood flow activity for about one square centimeter of brain surface. A small digital computer converts the data

provided by the detectors over a one minute period into a graphic image on a color-television monitor. The colors that are generated in each of the 254 squares of the image correspond to the intensity of the blood flow in that area. Intense activation generates white and red hues while strong inhibition produces a dark blue color.

Using this rCBF technology, Lassen, Ingvar, and Skinhøj (1978) have discovered some important aspects of normal brain processing during reading. Usually, this would not be possible because the radioactive isotope could not be introduced ethically to control subjects. However, in their research, Lassen, Ingvar, and Skinhoj came across a number of individuals who, despite preliminary indications, showed no abnormality on the rCBF scan or on EEG and other tests. These patients required cerebral arteriography and since the catheter for this test could be used to introduce the low level radioisotope with no independent risk to the patient, the rCBF scanning could be justified. These researhers report that 80 of the nearly 500 subjects scanned had a normal brain at the time of measurement, and therefore, could serve as controls.

One of the unexpected findings of the rCBF studies was that the right hemisphere played a far more active role during speech than had been indicated by the research of Broca and Wernicke. This outcome highlights the limitations inherent in inferring relationships exclusively on the basis

of tissue damage in an inanimate brain. In the original "brain tissue" studies, damage to right hemisphere sites that corresponded to Broca's and Wernicke's areas were not implicated in language dysfunction. By contrast, blood flow monitoring produced a sensitive account of expressive language processes in the living brain.

The blood flow studies also revealed that functional distinctions could be drawn between oral and silent reading processes. In simplest terms, the processes were less than identical. It was found that oral and silent reading shared certain cortical sites including the visual association area, the frontal eye field, the supplementary motor area, Broca'a area, and the primary visual cortex (which was not shown since the carotid artery does not project back to it). Oral reading caused greater activity to occur in the auditory cortex and in the mouth area of the motor cortex. The critical point here is that since oral and silent reading processes are not identical, the use of oral reading as a "window on the silent reading processes of the mind" may be a tenuous assumption.

The rCBF investigations of Lassen, Ingvar, & Skinhϕj (1978) reaffirmed Luria's (1980) twofold notion that complex processes such as reading are distributed in the brain rather than localized and that cortical zones contribute very specifically to the total processing system. Lassen, Ingvar, and Skinhϕj (1978) suggest various subroutines of

the system are mobilized with respect to the task at hand. In the complex task of reading, they suggest that "several circumscribed cortical regions are brought into action in a specific pattern."

More recently, Hynd, Hynd, Sullivan, & Kingsbury (1987) used inhalation of xenon 133 and a somewhat different monitoring system to investigate patterns of cortical activity in patients exhibiting two subtypes of developmental dyslexia. Specifically, a surface and a deep dyslexic were compared with age-matched controls on a silent reading task involving a narrative passage. The regional blood flow patterns, though based on such a limited sample, were nonetheless interesting. Hynd et al. found 1) that for fluent readers the pattern of general activation affected blood flow bilaterally, 2) that the percentage change in cerebral blood flow levels in both normal controls during reading was signficantly greater in the right hemisphere, 3) that the surface dyslexic experienced less activation during reading in the right hemisphere, and 4) that the deep dyslexic actually experienced a decrease in right hemisphere blood blow. The authors rightly caution against overgeneralization of these findings; however, the notions that the right hemisphere may be implicated in the processing of narrative text and that physiological distinctions might be drawn between dyslexics and controls and between suspected dyslexic subtypes are important and

warrant further study. To this end, Hynd, Rosenthal, and Huettner (1987) have already successfully applied rCBF technology to the matter of confirming bilateral activation in normal subjects reading narrative text.

Single Photon Emission Computed Tomography (SPECT). A final radioisotope brain scanning method combines the blood flow and reconstruction principles. Known as SPECT, this method provides more detail than rCBF and is a great deal less expensive than PETT scanning (Yingling, 1987). Like rCBF and PETT scanning, SPECT shows blood flow by imaging trace amounts of radioisotopes. With SPECT, however, the cost of operation is greatly reduced because commercially available radioisotopes can be used. This capability eliminates the need for a costly cyclotron ("SPECT Images'", 1987). Overall, SPECT is less versatile and accurate than PETT but its convenience, reconstruction dimension, and more moderate cost may give rise to increased usage. Presently there seem to be no reading-related studies reporting the use of the SPECT technology.

Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging is the latest and in many ways one of the most exciting of the brain scanning technologies. The method is wholly non-invasive, and therefore, safe and painless. In addition, it generates the clearest pictures to date. Yingling (1987) has suggested that MRI pictures contain such an enormous amount of detail

and spatial resolution that the output resembles anatomy book drawings. Because of their remarkable clarity, MRI scans promise new certainties in diagnosis (The Brain, 1982). MRI units primarily reveal structural abnormalities in the brain, and to a lesser extent, they indicate possible functional problems. This latter capability is actually a motion artifact derived from averaging and reconstructing scans (A. Mamourian, personal communication, October 27, 1987).

The MRI equipment consists of a tunnel-like system of tremendously powerful electromagnets, a radio-frequency generator, and a computer to evaluate the data. The electromagnets, supercooled to a temperature of -452 degrees Fahrenheit by liquid helium, surround the scanner and create a field whose strength can approach 60,000 times that of the earth. To be fully functional, the system must be completely shielded from external radio frequency interference. This requirement alone boosts the already prohibitive 1.8 million dollar price tag some three quarters of a million dollars higher (Sochurek, 1987).

Magnetic Resonance technology capitalizes on the principle that hydrogen atoms line up when subjected to a magnetic field. Hydrogen serves as an excellent basis for MRI scanning because of its prominent magnetic qualities and its abundance in the body. Inside the MRI scanner's electromagnetic field, protons (the nuclei of hydrogen

atoms) align themselves in the direction of the field's poles. The scanner then knocks the protons out of alignment with a precisely synchronized radio pulse. When the radio waves are discontinued, the protons realign themselves giving off a faint radio signal of their own as they spiral back into place. The computer transforms the faint radio signals to form a cross-sectional image that reflects the varying densities of hydrogen atoms and their interactions with surrounding tissues. To do so, it varies the magnetic field in three dimensions that roughly correspond to head to toe, dorsal to frontal, and left to right. Finally, the computer assigns the data to a spot on the video screen using different levels of brightness to indicate the number of protons and the magnetic properties of the tissue (Mamourian, personal communication, 1987; Sochurek, 1987; Yingling, 1987).

Very recently, MRI technology has been applied to the task of linking neurological abnormalities with severely reading disabled individuals (Caffara, 1987; Momose, Yoshikawa, Bandoh, Iwata, & Iio, 1986; Rumsey, Dorwart, Vermess, Denckla, Kruesi, & Rapoport, 1986; Sugishita, Yoshioka, & Kawamura, 1986). Thus far, Rumsey et al. (1986), using MRI, found clinically normal brain anatomy in 9 of 10 men exhibiting chronic severe developmental dyslexia. Their intent was to note pathology not revealed in previous computed tomographic scan studies. The MRIs

scans did confirm the notion that developmental dyslexia seems associated with temporal lobe symmetries but the scans did not identify a common focal pathology despite the documented sensitivity of the system. In light of these findings, Rumsey et al. (1986) concluded that MRI may prove useful for studying macroscopic asymmetries in dyslexia.

The majority of other studies using MRI technology with dyslexics focus on only one or two subjects. This trend toward case reports is not surprising given the relative newness of the system and the fact that the long range health effects of MRI scanning are not yet known. So unless there is another reason to warrant scanning, even this seemingly safe technology cannot be used with larger numbers of subjects, especially controls.

In these small scale MRI studies, structural abnormalities have been associated with severe language disorders such as alexia, callosal disconnection, and hemialexia. Caffarra's (1987) findings with an alexic subject lent credence to the notion that the anatomic pathways responsible for reading run close to the lateral temporo-occipital gyrus. Sugishita, Yoshioka, and Kawamura (1986), in their work with a hemialexic subject, expected to find a splenial lesion based on knowledge that a pineal tumor had been surgically removed nine years earlier. Instead, MRI scans showed clearly that the splenium was not present. Lastly, Momose, et al. (1986) studied two cases of

callosal disconnection resulting from cerebral infarction. In both instances, the subjects' corpus callosums were found to be intact; however, five other areas were shown to be involved similarly across both subjects. While certain of the scans did not provide sufficient information to study disconnection syndromes, other reconstructions demonstrated the relationship of lesions to the adjacent structure of cerebral white and gray matter. Momose, et al. (1986) concluded that MRI may prove to be a most useful tool in the study of interhemisperhic information transfer.

In the near future, it is expected that MRI units will be able to scan other elements such as phosphorus. Some preliminary work has been done with animals in this regard (Lugeti, Barlow, Chance, Kovach, & O'Connor, 1983). When this capacility is achieved, greater monitoring of metabolism will be permitted. As a result, it may be possible to detect subtle differences in brain chemistry and tissue that may be indicative of severe reading difficulties.

Brain Wave Monitoring

Brain Electrical Activity Mapping (BEAM). Other techniques for monitoring brain function rely on the principle that electrical signals ripple across the brain as millions of neurons fire repeatedly. Since 1929 when German psychiatrist, Hans Berger, first recorded human brain waves, the technology known as electroencephalography has become

increasingly more refined and useful. In standard electroencephalography, wires are placed at carefully measured intervals on the subject's scalp. The wires, in turn, feed into an amplifier that magnifies the signals so that the impulses can be traced on paper as rows of oscillating waves. Several researchers using EEG technology have unearthed evidence that associates brain wave aberrances with dyslexia (Ayers & Torres, 1967; Buchsbaum et al., 1982; Hanley & Sklar, 1976; Hughes, 1978; Hughes & Park, 1969; Sobotka, & May, 1977; Symann-Louett, Gascon, Matsumiya, & Lombroso, 1977; Torres & Ayers, 1968); however, the evidence has not been universally embraced (Hynd & Hynd, 1984).

The brain electrical activity mapping (BEAM) technology introduced by Frank Duffy of Harvard University merely enhances the usefulness of information already available on a standard electroencephalograph (EEG). Interpreting the massive amount of data yielded by an EEG requires spatial, temporal, spectral and statistical analyses of the brain waves appearing on the recording (Restak, 1984). Even then, the electrical "noise" of the brain is so intense that certain of its crucial messages become obscured. The BEAM computer automates the analyses by converting the squiggly lines of the EEG into a contour color-coded map of the electrical activity at the surface of the brain. The graphic that ensues is far more easily interpreted and

retained by the examiner than conventional EEGs. Interestingly, the method does not include any more raw data than the EEG; it simply extracts greater amounts from the minute electrical voltages generated by the 10 billion nerve cells below. In this way, brain electrical activity mapping increases the utility of the basic technology underlying standard 20-channel EEG technology (Duffy, Burchfiel, & Lombroso, 1979; Restak, 1984; Torello & Duffy, 1985)

In the BEAM system a high speed computer transforms the seemingly erratic EEG tracings into sharp-edged, often concentric "islands" of brilliant hues on a monitor. The patterns, which resemble rainbows, "expand and contract, ebb and flow, and even bounce off the inner boundaries of the head" (McKean, 1981). The striking images greatly reduce the need for the interpreter of the data to envision mentally the topographical representation of the brain's activity.

There are advantages and disadvantages to using the BEAM technology. On the plus side, the procedure is non-invasive; that is, unlike technologies that involve injecting radioactive substances into the blood stream, the BEAM computer monitors electrical activity at the surface of the brain, totally outside the head. Clinical subjects encounter zero risk. The notion that monitoring occurs only at the surface of the brain also accounts for the down side of the BEAM system. Dependent on the sensitivity of

standard EEG technology, the BEAM computer receives electrical signals from the surface of the brain that are muffled by the skull. The resulting scenario for monitoring is likened to attempts to overhear a conversation at a loud party through a wall. And so the challenge for the BEAM computer is to take a subtle signal and to display it in high contrast (Restak, 1984).

The field of reading has already benefitted from the BEAM technology. Studies comparing dyslexic and normal boys have yielded characteristic patterns of brain waves that can be accurately associated with the disability 80 to 90% of the time (Duffy, Denckla, Bartels, & Sandini, 1980; Duffy, Denckla, Bartels, Sandini, & Kiessling, 1980; Restak, 1984). Identification of dyslexia using BEAM is made possible because there seems to be a reasonably distinct electrical profile or signature to which the apparatus is sensitive. From their research with dyslexics, Duffy and his colleagues conclude that dyslexics do not efficiently use the interrelated regions of the brain thought to be important in reading (i.e., the angular gyrus, Wernicke's area, the arcuate fasciculus, Broca's area). Further, these researchers suggest that true dyslexia seems less associated with a discrete brain lesion than with dysfunctions occurring within a complex and widely distributed system (Hynd & Hynd, 1984). A somewhat unexpected, yet interesting theoretical finding was that dyslexics seem to evidence

stronger alpha waves in the supplementary motor area, located in the upper portions of the frontal lobe. This area is known to help in the planning of complex motor activity. Since alpha waves signal brain inactivity (Davidson & Schwartz, 1977; Gevins, et al.), it is likely that in dyslexics the supplementary motor area is not as vigorous as it ought to be in reading (McKean, 1981).

The major benefit of identifying characteristic patterns of brain waves in dyslexics is that early diagnosis appears to be possible. At-risk children could be detected, perhaps even before starting school, and appropriate preventitive measures could be initiated. Furthermore, brain electrical activity mapping imposes no cultural bias on the data. As a result, it faithfully identifies at-risk children with considerable precision regardless of the native language that they speak. Similarly, despite evidence that suggests dyslexia is not a "disease" with a unitary symptom, BEAM reliably confirms the results of neuropsychological tests regardless of suspected subtype. A key advantage of the neurophysiological BEAM assessment is that it can detect changes in brain function that may not be apparent behaviorally when the neuropsychological batteries are administered (Torello & Duffy, 1985). Collectively, then, BEAM's ability to recognize existing and potential learning disabilities may preclude children from having to

experience the major psychological trauma normally associated with these deficits.

Compared to many contemporary brain monitoring devices, BEAM systems are relatively inexpensive ($50,000). In addition, according to Yingling (1987), BEAM can be implemented on an IBM personal computer and possesses the best temporal resolution by virtue of delays lasting only milliseconds. Restak (1984) might take issue with the temporal resolution claim, instead singling out technology developed by Jesse Salb of Diasonics, Incorporated. In Salb's system the resulting color maps are produced in such a way that the brain's electrical potentials are recorded and displayed faithfully in real time. Like BEAM, Salb's system monitors the electrical activity of the brain and a computer produces images on an anatomical map of the head. However, Salb's system uses a greater number of electrodes and they are placed at strategic positions over the entire scalp to produce the moving images. In this system, like BEAM, different colors represent variable levels of electrical activation.

Eye Tracking

The last technology to be discussed, eye tracking, departs noticeably from the neuroimaging technologies in that it makes no attempt to examine the internal structure or workings of the brain. Instead, the eye tracker monitors eye fixations in reading, an indirect indication of brain

activity. The rationale underlying this paradigm is that gaze durations, the amount of time spent in consecutive fixations on the same word, reflect the internal cognitive processes of the reader. The primary proponents of this paradigm, Marcel Just and Patricia Carpenter of Carnegie-Mellon University provide detailed support for their assumptions of immediacy (interpretations at all levels of processing occur as quickly as possible) and eye-mind (the eye remains fixated on a word for the duration of its processing) by integrating and reconciling findings from a wealth of empirical studies of reading and language processes including personal experiments conducted in their research laboratory (See Just & Carpenter, 1980, 1987 for a detailed account).

The research laboratory at Carnegie-Mellon represents a sophisticated application of engineering technology. Their eye tracker is a recent addition to a long line of systems designed to measure eye movements in reading. The psychological sciences have evidenced a rather extensive history of making such measurements during reading (Buswell, 1922; Erdmann & Dodge, 1898; Huey, 1908; Javal, 1879; McConkie & Rayner, 1976; Tinker, 1933, 1947, 1958). Nevertheless, from the dual standpoints of precision and unobtrusiveness, Just and Carpenter's eye tracker represents state-of-the-art equipment. Extremely accurate measurements

can be made without subjecting individuals to cumbersome, unnatural, or uncomfortable conditions for reading.

The apparatus monitors the eye movements of an individual reading from a computer-controlled videoscreen. The reader is seated comfortably and naturally in an armchair some 20 inches away from the screen. The armchair's headrest supplies support and stabilizes head movements. Situated to the left of the screen are the three components of the optical part of the tracker: a light source, a mirror and a videocamera. The tracker operates on the premise that light aimed at the reader's eyes will be reflected back from the cornea. Because rotations of the eye cause the reflection of the light source to move as well, it is possible to detect within 1 degree of horizontal and 1.5 degrees of vertical angle what elements of the text are being fixated. To allow for the lower precision associated with the vertical measurement, the screen display appears in a doublespaced format. The visual angle of the print and the type font resemble those occurring in typical reading scenarios, especially CRT presentations.

A low-intensity, infrared light, coaxial with the videocamera lens, illuminates one of the reader's eyes. In turn, light reflected from the cornea and pupil is recorded by the videocamera. The signal from the videocamera is then converted into a digital format by an electronic device that also serves to preprocess the signal and to recognize both

the outline of the pupil and the reflection of the cornea. A minicomputer calculates the reader's point of regard by processing the digital data associated with the video image. At a rate of 60 video fields per second, the tracker determines the reader's fixation point and forwards the data to a DEC MicroVAXII laboratory computer. The laboratory computer collects the eye-fixation data and stores it for subsequent inspection (Just & Carpenter, 1987).

The primary advantages of this particular eye tracking technology are its sensitivity to individual differences in readers' reflection/location parameters, and secondly, its accommodation for their head movements. The first potential source of misinformation is controlled by pre-assessing each reader's corneal reflection patterns over nine predetermined location points on the videoscreen. Head movements are accommodated in the measurement by employing a second reference point, the position of the center of the pupil, and by a servo-controlled mirror through which the videocamera observes the eye. When the reader's pupil moves across a boundary of the camera's viewing field, the mirror is automatically repositioned to recenter the pupil in the field. Collectively, the pupil reference point and the mirror allow accurate measurement to occur within a tolerable head movement range of 36 square inches.

This impressive piece of equipment helps to evaluate reading theory by monitoring a physiological product of

underlying brain operations. The brain directs the eye in response to the reading task at hand. This eye-mind paradigm opens numerous avenues for examining the impact of a multitude of both text and reader variables. Just and Carpenter (1980, 1987) have already set forth a theory of reading that can be evaluated with the use of this technology. These researchers in conjunction with their colleague, Robert Thibadeau, have also created artificial intelligence systems for a computer that is designed to mirror the time course of reading certain kinds of text (Thibadeau, Just, & Carpenter, 1982). By comparing the "human" data obtained from the eye tracker with the data obtained from the artificial intelligence runs, the fit of the reading model can be roughly estimated. Thus far, the reading model accounts for fully 79% of the variance associated with reading a scientific text. Obviously, this constitutes a most noteworthy fit. Natural extensions of this line of research include programming the system for speedreading and to account for individual differences in knowledge structures and reading strategies. By studying the temporal course of various reading processes such as encoding and lexical access, this artificial intelligence paradigm figures to shed light on how the processes are organized and coordinated (Thibadeau, Just, & Carpenter, 1982).

Conclusion

The accounts of the various technologies outlined here make it clear that the field of reading has already profitted immensely from their inception and implementation. We have a greater understanding not only of speech mechanisms and oral and silent reading, but also of structural and functional patterns underlying dyslexia. However, one senses that we are merely scratching the surface. Newer, even more impressive apparatuses and research paradigms for studying the reading process await.

For the time being, alterations in the use of existing technologies also offer the promise of supplying additional information. For instance, one alteration might be to vary radioactive tracers in PETT scans. In this way, we would acquire new and diversified pictures of the same event. Another alteration would be to combine scanning paradigms just as SPECT was conceived by coupling the reconstruction and blood flow principles. To date, PETT scans and BEAM technologies have been combined successfully to yield greater diagnostic precision and John Morihisa and colleagues at the National Institute of Mental Health are experimenting with linking BEAM technology with yet another instrument to monitor blood flow in the brain (Restak, 1984). George and Cynthia Hynd of the University of Georgia and their colleagues are now mapping brain electrical activity during the reading of various kinds of text and

looking for discernible patterns (G. Hynd, personal communication, November 3, 1987). Like any form of diagnosis, the validity and reliability of future assessments will be enhanced when multiple sources of data are viewed in tandem (Henk, 1987). The collective data pool of many technologies and their combinations will expand the perspectives from which reading disabilities can be viewed and evaluated.

To this end, it is foreseeable in future reading diagnoses that eye trackers may be coupled with non-invasive neuroimaging technologies that shed light on the inner workings of the brain. These eye-brain devices will generate an even more elaborate account of the reading process than either technology could produce alone. Such a marriage would permit researchers to note the correspondence between what a reader views and the internal cognitive processes that are being executed simultaneously. This combination of technologies alone would probably revolutionize the study of reading processes by greatly reducing our reliance on the black box approach to inquiry. Controversies regarding reading readiness, dyslexic typologies, and the effectiveness of various and sundry instructional methodologies might be resolved. Direct examination of the influence of a multitude of text variables could be obtained. Specific neural pathways of lexical access might be delineated. Individual reader

differences could be discerned. The possibilities are at once exhilarating and overwhelming.

Because of the new technologies, reading educators may soon engage in a more productive collaborations with neuroscientists. As Chall and Mirsky (1978) suggest, the collaboration must be mutual; that is, neurological hypotheses must be tested and applied in classrooms and clinics and educational research must be routed back to the neuroscientists for theory refinement. Further, the collaboration should extend to a team of specialists including educational psychologists, neuropsychologists, linguists, resource room teachers, anthropologists, guidance counselors, opthalmologists, and speech therapists to name just a few. The combined expertise of these professionals along with the specific and exhaustive data yielded by the new technologies promise to usher in an unparalleled diagnostic precision and subsequent personalized instruction. Input about the efficiency of sensory modalities, brain development and chemistry, mechanisms of attention, and latent neural activity will clearly open up new evaluative and pedagogical vistas.

At the same time, we must resist the urge to be swept away by our enthusiasm. Although the newer technologies represent a major step forward, they will not provide all the answers that we seek in reading education. Individual assessments, however precise and far-reaching, will reveal

little about important group processes and settings that bear heavily on the learning process. So while learning is undeniably an internal function of the individual, its facilitation must occur against the backdrop of the classroom, a microcosm of extensive and complex social dynamics. Answers regarding optimum grouping procedures, classroom management, discipline, and the like almost surely lie outside the realm of the new technologies. Viewed in this sense, the technologies are tools that will simply help reading professionals do their job better; they are by no means a panacea.

Their limitations notwithstanding, following the progress of technological advances in the monitoring of reading processes over the next decade or so will be a most fascinating venture. One by one, many of our intuitions about the nature of the reading process, its diagnosis, and its facilitation should give way to verifiable truths. As a discipline, then, the field of reading is clearly on the eve of one of the most exciting eras in its long history.

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Footnotes

[1] This argument is not intended to diminish the contribution of historical or contemporary post-mortem studies to our understanding of language disabilities. Post-mortem studies have revealed abnormalities in the morphology of the brain that have provided and continue to provide a focus for neuroimaging (Hynd & Semrud-Clikeman, 1987a; 1987b).

[2] The author would like to express appreciation to Dr. George Hynd and Dr. Cynthia Hynd, both of the University of Georgia, for their assistance in the preparation of this paper. Likewise, the contribution of Dr. Alex Mamourian, radiologist at the Magnetic Resonance Imaging facility of the Milton S. Hershey Medical Center, is also heartily acknowledged.